Laser emissions from one-dimensional photonic crystal rings on silicon-dioxide
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Mode switching and beam steering in photonic crystal heterostructures implemented with vertical-cavity surface-emitting lasers
Two-dimensional photonic crystal ring resonators (2D PhCRRs) have been widely applied for constructing versatile photonic integrated circuits (PICs) via proper bus photonic crystal (PhC) waveguides. Comparing with traditional microring resonators, light can operate at slow light region or recycle with low loss via photonic band gap effect in 2D PhCRRs with compact ring sizes, which are beneficial for efficient lasers in PICs. In addition to lasers, a variety of functional devices based on 2D PhCRRs, such as add-drop filters, logical units, optical buffers, and sensors, have also been proposed and demonstrated recently. However, using 2D PhCs leads to large device footprint, and the lattice geometry restricts the integration ability. Although micro-disks (MDs) with different periodic nanostructures can overcome these drawbacks owing to their small device footprints and capabilities for ridge waveguide coupling, the high-order modes in MDs still blemish them for serving as lasers. Another feasible solution is encircling 1D PhC nanobeam (NB), a ridge waveguide with 1D PhCs widely investigated recently for constructing low-loss resonators to form 1D PhCRR as shown in Fig. 1(a). 1D PhCRR has small device footprint and high integration flexibility in PICs via ridge waveguide coupling without PhC lattice geometry restrictions. Recently, 1D PhCRRs have been studied in slow light applications, while the other applications are still scarce in the literatures. In this report, we design 1D PhCRRs on SiO2 to realize InGaAsP/SiO2 hybrid lasers. Single-mode lasing from the dielectric mode is obtained. To further design a nanocavity with mode gap effect in 1D PhCRR results in the reduced lasing threshold and increased vertical laser emissions, owing to the reduced dielectric mode volume and the broken rotational symmetry by the nanocavity. Such hybrid lasers based on 1D PhC rings provides good geometric integration ability and new scenario for designing versatile devices in photonic integrated circuits. © 2013 American Institute of Physics.
Fig. 2(a), which both increase with $P$ owing to the decreased bend loss of the enlarged ring size. Then, with fixed $P$ of 28, the influences of $r/a$ and $w$ on $Q$ and $\gamma_d$ factors are investigated individually. In Fig. 2(b), with fixed $w$ of 1.3$a$, both $Q$ and $\gamma_d$ factors increase when $r/a$ decreases because of the increased effective index. Likewise, in Fig. 2(c), with fixed $r/a$ of 0.27, both $Q$ and $\gamma_d$ factors increase with $w$ owing to the increased effective index. When $w > 1.1a$, $Q$ and $\gamma_d$ factors larger than 2000 and 0.4 are sufficient for lasing.

The first step of the fabrication process shown in Fig. 3 to realize 1D PhCRR on SiO$_2$ is transferring III-V active material, a compressive-strained InGaAsP multi-quantum-wells (MQWs) on InP with InGaAs etching stop layer, denoted as wafer $A$ in Fig. 3, onto SiO$_2$. The thickness and photoluminescence peak of MQWs are 190 nm and near 1550 nm. MQWs and a silicon (Si) wafer (denoted as wafer $B$ in Fig. 3) are both deposited 800 nm SiO$_2$ layers by plasma enhanced chemical vapor deposition (PECVD) at 80 $^\circ$C. Subsequently, we joint these two wafers via DVS-bis-benzocyclobutene (BCB, Cyclotene-4022-35, Dow Chemical Company) adhesive bonding technique, 23, 24 as illustrated below in details:

1. The BCB is spin-coated (6000 rpm for 240 sec) on MQWs and Si wafers with SiO$_2$.
2. The two wafers are pre-cured at 60 $^\circ$C for 4 min and then clamped together under uniform pressure of 130 kPa at 250 $^\circ$C for 2 h.

With diluted BCB (mesitylene: BCB = 1:3), after step 2, the thickness of BCB adhesive layer is as thin as 200 nm, shown as the inset cross-sectional scanning electron microscope (SEM) picture in Fig. 3. The InP substrate of MQWs, InGaAs etching-stop, and InP capping layers are removed via diluted HCl, solution of H$_3$PO$_4$/H$_2$O$_2$/H$_2$O = 1:1:8, and diluted HCl wet etching at room temperature in sequence to leave MQWs on SiO$_2$. Then the MQWs on SiO$_2$ are followed by a series of nanofabrication process illustrated below to manufacture PhC nanostructures.

1. Deposit 70 nm SiNx hard mask on MQWs by PECVD.
2. Spin-coat 240 nm electron-beam (e-beam) resist (poly-methylmethacrylate, PMMA) on SiNx hard mask.
3. Define PhC patterns on PMMA via e-beam lithography.
4. Transfer PhC patterns from PMMA to SiNx hard mask and MQWs in sequence via reactive ion etching and inductively coupled plasma dry etching at room temperature.

![Fig. 2. Theoretic $Q$ and $\gamma_d$ factors of the dielectric modes in 1D PhCRRs on SiO$_2$ as (a) a function of $P$ from 12 to 48 under fixed $w$ and $r/a$ ratio of 1.3$a$ and 0.27, (b) a function of $r/a$ ratio under fixed $P$ and $w$ of 28 and 1.3$a$, and (c) a function of $w$ under fixed $P$ and $r/a$ ratio of 28 and 0.27. The parameters $t$ and $a$ are fixed at 190 and 400 nm in (a)-(c).](image)

![Fig. 3. Flow chart of manufacturing 1D PhCRRs on SiO$_2$. The inset SEM picture shows the cross-section of the BCB bonding interface.](image)

![Fig. 4. (a) Top- and (b) tilted-view SEM pictures of 1D PhCRR with $P$ = 28.](image)
invariant theoretic wavelengths (0.3 nm difference), $Q$s (7% difference), and dielectric modes profiles in 1D PhCRRs with and without the surrounding patterns via 3D FEM.

We then characterize 1D PhCRR shown in Fig. 4 via diode laser pulse with wavelength of 845 nm, 2% duty cycle, and spot size of 6 $\mu$m in diameter. Single-mode lasing spectrum at wavelength near 1538 nm with side-mode suppression-ratio (SMSR) of 25 dB are obtained and shown in Fig. 5(a). Unlike the MDs with periodic nanostructures, only one mode has sufficient $Q$ for lasing in 1D PhCRR. A lasing threshold of 0.57 mW (effective threshold $/C^2$) is estimated from the light-in light-out (L-L) curve shown in Fig. 5(b). Moreover, dissimilar to highly linear-polarized laser emissions of the dielectric modes in 1D PhC NB, the emissions from 1D PhCRR exhibit a low polarized degree ($P_D$) of 2.3, shown in the inset of Fig. 5(b). Owing to the rotational symmetry of the ring, $E_x$ and $E_y$ fields of the dielectric mode in 1D PhCRR are identical, which means the laser emission is dominated by neither $E_x$ nor $E_y$ fields and should be un-polarized ideally. $P_D > 1$ in experiments is attributed to the fabrication imperfections of the characterized device. In addition, we also demonstrate 1D PhCRRs with different $P$. Single-mode lasing from the dielectric mode can be still observed when $P = 24$ only, whose device footprint is as tiny as $21 \mu m^2$.

Comparing with the traditional microring resonators, in addition to the slow light effect mentioned before, the other significant benefit of 1D PhCRR is that the mode properties can be altered via purposely tuned PhCs. To show this feature, we linearly shrink the air-hole radii of 1D PhCRR under fixed $a$ of 400 nm from the top ($r$) to the side region ($r'$), as shown in Fig. 6(a). This forms a 1D PhC nanocavity (1D PhC-nc) with mode gap effect, where $\Delta r/a$ is defined as $r/a - r'/a$. In Fig. 6(b), with $\Delta r/a$ of 0.02 and the same parameters as for 1D PhCRR, the dielectric mode in 1D PhC-nc shows significant field enhancement in the cavity region than that in PhCRR, which leads to a reduced $V_{eff}$ of 1.7 $(/R_{InGaAsP})^3$ while there are no significant reductions in $Q$ ($\sim 5700$) and $/d$ ($\sim 0.456$) factors.

In measurements, single-mode lasing with SMSR over 30 dB is observed from 1D PhC-nc on SiO$_2$ with $\Delta r/a$ of 0.02 and the same parameters as for 1D PhCRR, as shown in Fig. 5(a). The lasing wavelength of 1D PhC-nc near...
1546 nm shows a red shift of 8.0 nm than that of 1D PhCRR, which agrees well with the theoretic value of 11.4 nm via 3D FEM. More noteworthy is that the L-L curve of 1D PhCr-nc in Fig. 5(b) shows a lower threshold of 0.46 mW (effective threshold \( \sim 29 \mu W \)) and larger slope efficiency than those of 1D PhCRR. With almost the same \( Q \) and \( \gamma_d \) factors of the dielectric modes in 1D PhCRR and PhCr-nc, smaller \( V_{ef}{ }^{\text{eff}} \) in 1D PhCr-nc means larger Purcell factor, that is, stronger coupling between spontaneous emission and lasing mode, which leads to lower threshold of 1D PhCr-nc than that of PhCRR. In addition, the existence of nanocavity leads to the rotational symmetry breaking and changes the far-field profile of the dielectric mode, thus resulting in more vertical emissions and larger slope efficiency of 1D PhCr-nc than those in 1D PhCRR. Moreover, the laser emissions from 1D PhCr-nc also exhibit a low PD of 1.5, shown in the inset of Fig. 5(b). This is because neither \( E_x \) nor \( E_y \) fields significantly dominate the dielectric mode in 1D PhCr-nc. Furthermore, the thresholds of 1D PhCRRs and PhCr-ncs with different \( w \) and \( r/a \) are shown in Figs. 6(c) and 6(d). The thresholds of 1D PhCRRs are always higher than those of 1D PhCr-ncs, owing to their differences in \( V_{ef}{ }^{\text{eff}} \) of the dielectric modes as mentioned before. The thresholds of 1D PhCRRs and PhCr-ncs both decrease with decreasing \( r/a \) and increase with decreasing \( w \), which strongly correlate with the variations of \( \gamma_d \) factors under different \( r/a \) and \( w \) shown in Figs. 2(b) and 2(c).

To know the long term stability of 1D PhCRR and PhCr-nc, the devices are excited continuously for 6 h by fixed pump power of 1.5 mW. Lasing wavelengths and linewidths of 1D PhCRR and PhCr-nc as functions of excitation time \( t \) are shown in Fig. 6(e). After 6 h, both of them show slight blue shifts of 0.2 nm in lasing wavelength owing to the surface oxidation of InGaAsP and almost invariant linewidths. The lasing spectra of 1D PhCRR and PhCr-nc at \( t=0 \) and 6 h are shown in Fig. 6(f). These results not only show the long term stabilities of lasing from 1D PhCRR and PhCr-nc but also confirm the thermal stability of the BCB adhesion layer under present pump condition.

In summary, we have proposed and investigated the dielectric mode properties in 1D PhCRR on SiO\(_2\). Via BCB adhesive bonding technique and a series of nanofabrication process, the designed 1D PhCRR is utilized to demonstrate InGaAsP/SiO\(_2\) hybrid lasers with low effective threshold (\( \sim 36 \mu W \)) and small device footprint. To further design a nanocavity with mode gap effect in 1D PhCRR to form a 1D PhC-nc will result in the reduced lasing threshold (\( \sim 29 \mu W \)) and increased vertical laser emissions owing to the reduced dielectric mode volume and the rotational symmetry breaking by the nanocavity. In addition, the long term stabilities of lasing from 1D PhCRR and PhCr-nc are also confirmed. We believe this kind of resonators based on 1D PhCRR with small device footprints and good integration ability without lattice geometry restriction can provide new scenarios as efficient active light sources and other functional passive devices in versatile PICs.

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